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Potential Climate Change Impacts on the Hydrological System of the Harvey River Catchment

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***Abstract*—**Climate change is likely to impact the Australian continent by changing the trends of rainfall, increasing temperature, and affecting the accessibility of water quantity and quality. This study investigates the possible impacts of future climate change on the hydrological system of the Harvey River catchment in Western Australia by using the conceptual modelling approach (HBV mode). Daily observations of rainfall and temperature and the long-term monthly mean potential evapotranspiration, from six weather stations, were available for the period (1961-2015). The observed streamflow data at Clifton Park gauging station for 33 years (1983-2015) in line with the observed climate variables were used to run, calibrate and validate the HBV-model prior to the simulation process. The calibrated model was then forced with the downscaled future climate signals from a multi-model ensemble of fifteen GCMs of the CMIP3 model under three emission scenarios (A2, A1B and B1) to simulate the future runoff at the catchment outlet. Two periods were selected to represent the future climate conditions including the mid (2046-2065) and late (2080-2099) of the 21st century. A control run, with the reference climate period (1981-2000), was used to represent the current climate status. The modelling outcomes show an evident reduction in the mean annual streamflow during the mid of this century particularly for the A1B scenario relative to the control run. Toward the end of the century, all scenarios show a relatively high reduction trends in the mean annual streamflow, especially the A1B scenario, compared to the control run. The decline in the mean annual streamflow ranged between 4-15% during the mid of the current century and 9-42% by the end of the century.

***Keywords*—**Climate change impact, Harvey catchment, HBV model, hydrological modelling, GCMs, LARS-WG, Australia.

I. Introduction

WATER is considered as a vital source in the world, and it has a significant economic, environmental and social values which are growing rapidly [1]. Since the early 1970s, a large part of Australia, especially Western Australia (WA), has experienced a dryer climate which reduced the amount of annual rainfall and in turn badly impacted the availability of water resources in the area [2]. This shift in climate conditions was widely acknowledged by the hydrologic researcher community as in [3]-[9]. The Intragovernmental Panel on Climate Change in its Fourth Assessment Report (IPCC, AR4) classified Perth and its outskirts as highly vulnerable areas to a water supply deficiency in the next decades as a consequence of the future climate variations [10]. In addition to the water reduction problem, the rapid economic and population growth in the area has drawn concerns of researchers and policy makers about the future water availability and its sufficiency to meet the new water requirements. Therefore, valuable and efficient water management strategies need to be adopted in the region to overcome this problem.

Impact assessment studies widely use the hydrological simulation procedure to investigate the influence of climate change on catchment hydrology. Climate outputs extracted from the analysis of General Circulation Models (GCMs) are the key input to the process-based simulation models. References [11] and [12] explained that the GCMs are the most reliable tool for regional and global climate predictions. However, [13] showed that the uncertainty of climate change predictions is varied with the region and type of the model used, and may lead to a high ambiguity in future climate estimations. Furthermore, the climate series outputs resulting from the GCMs are not appropriate to be used directly in a catchment scale hydrological modelling because of their course spatial resolution and need to be downscaled prior to the modelling process [14], [15]. Many downscaling techniques have been used around the world to extract the local-scale climate signals from the global-scale of the GCMs outputs [16]-[18]. Furthermore, numerous hydrologic impact studies with a diversity of environment have been done globally to investigate the impacts of climate change on the accessibility of future water resources [19], [20]. In Australia, almost all the impact assessment studies warned from inevitable decline trends in future rainfall and consequently less runoff to the main water streams [21]. Therefore, this most likely reduction in the future rainfall needs reliable water management strategies to ensure the best allocation of the future water resources.

This study aims to assess the hydrological behavior of the Harvey River catchment in WA under a changing climate. The mid (2046-2065) and late (2080-2099) of the 21st century were used to represent the future climate conditions. Future climate signals were derived from a multi-model ensemble of fifteen GCMs of the CMIP3 under three emission scenarios (A2, B1 and A1B) which belong to the IPCC-AR4. The Long Ashton Research Station Weather Generator, version 5.5 (LARS-WG5.5), a stochastic weather generator, was used to extract the local-scale of rainfall and temperature from the global-scale of the GCMs output. The HBV conceptual rainfall-runoff model was used to perform the hydrological modelling to simulate the future daily streamflow at the catchment outlet

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using the daily values of rainfall and temperature and the long-term monthly mean potential evapotranspiration as input data. Hence, the outcomes of the present work could deliver efficient water management strategies for the study area to overcome the problem of water scarcity.

II. Harvey River Catchment

The Peel-Harvey catchment, with an entire approximate area of 1.15 million hectares around the Serpentine, Harvey and Murray Rivers system, is located about 80 kilometers south of Perth city (Fig. 1) [22]. The area has a growing economic, environmental and cultural importance in WA. The main focus area of the present study is the Harvey River catchment which stretches from the latitude of 32.35°-33.15° S and longitude of 115.40°–116.10° E with an approximate total drainage area of 1329 km^2. The catchment was divided into four main sub-catchments namely Harvey reservoir, Meredith drain, Mayfield drain and Harvey as illustrated in (Fig. 1). The climate of the catchment is Mediterranean with a summer season tends to be hot-dry and winter season tends to be cold-wet. The temperature is nearly ranged between 10 to 18 °C in the winter, and it approximately between 18 to 28 °C in the summer and sometimes reaches 40 °C [22]. The period between April and October almost hold 90% of the total yearly rainwater fallen on the catchment. High precipitation area of the catchment is located on the scarp in which the average annual precipitation ranged between 900-1300 mm over the coastal plain. The eastern part of the catchment receives the lowest rainfall amounts in which the precipitation decreases to around 450 mm/year [23].

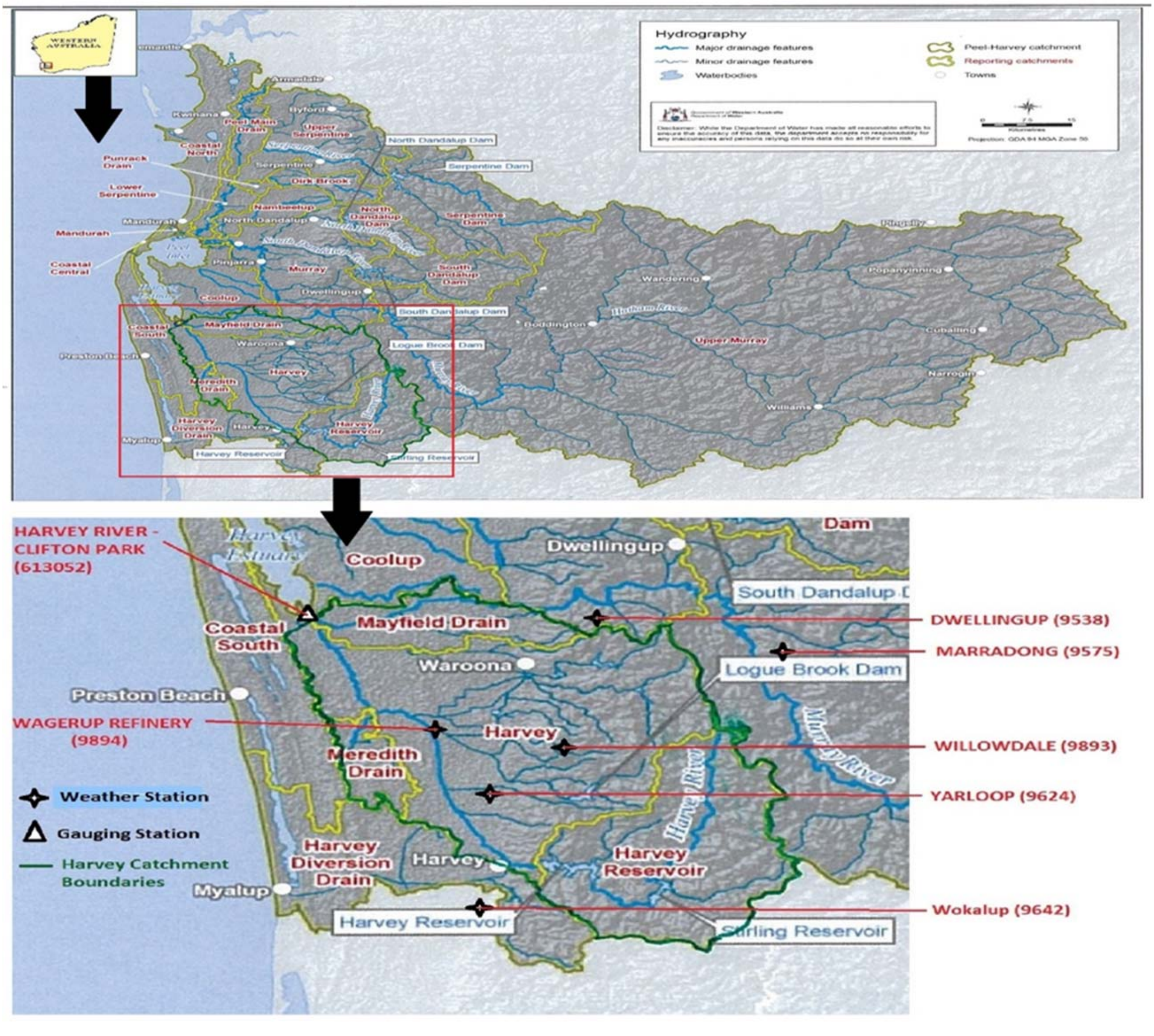


Fig. 1 Harvey Catchment with the weather and streamflow gauging stations [24]

III. Data and Hydrological Modelling

A. Observed Climate Data

The observed climate and streamflow data (rainfall, temperature, potential evapotranspiration and discharge) were acquired from seven hydro-meteorological stations (Fig. 1). The names, locations and the observed parameters of each station are illustrated in Table I. The observed meteorological data were obtained from the Australian Bureau of Meteorology, and the quality of data has been checked with higher priority. Daily observed mean values of rainfall and temperature, from six weather stations, and the long-term monthly mean potential evapotranspiration from Dwellingup and Wokalup weather stations over the period (1961-2015) were used for the hydrological simulation. In addition, the high-quality daily recorded discharge, from the Department of Water, at Clifton Park gauging station on Harvey River for the period (1983-2015) was used to calibrate and validate the HBV-model prior to the streamflow prediction. The spatial distribution of rainfall and temperature over the whole basin was obtained from Thiessen polygon method.

TABLE I
Locations Of the Hydro-Meteorological Stations

Meteorological Stations	Station No.	Latitude (S°)	Longitude (E°)	Observed Parameter(s)
Dwellingup	9538	32.71	116.06	Rainfall, Temperature and evapotranspiration
Marradong	9575	32.86	116.45	Rainfall
Wagerup Refinery	9894	32.92	115.92	Rainfall
Willowdale	9893	32.92	116.01	Rainfall
Wokalup	9642	33.13	115.88	Rainfall, Temperature and evapotranspiration
Yarloop	9624	32.96	115.90	Rainfall
Hydrological Stations				
Harvey River - Clifton Park	613052	32.82	115.74	Discharge

TABLE II
The 15 Global Climate Models of the CMIP3 used in the present study

Research Centre	Country	Model ID	Abbreviation	Grid resolution
Commonwealth Scientific and Industrial Research Organisation	Australia	CSIRO-MK3.0	CSMK3	1.9 × 1.9°
Canadian Centre for Climate Modelling and Analysis	Canada	CGCM33.1 (T47)	CGMR	2.8 × 2.8°
Institute of Atmospheric Physics	China	FGOALS-g1.0	FGOALS	2.8 × 2.8°
Centre National de Recherches Meteorologiques	France	CNRM-CM3	CNCM3	1.9 × 1.9°
Institute Pierre Simon Laplace	France	IPSL-CM4	IPCM4	2.5 × 3.75°
Max-Planck Institute for Meteorology	Germany	ECHAM5-OM	MPEH5	1.9 × 1.9°
National Institute for Environmental Studies	Japan	MRI-CGCM2.3.2	MIHR	2.8 × 2.8°
Bjerknes Centre for Climate Research	Norway	BCM2.0	BCM2	1.9 × 1.9°
Institute for Numerical Mathematics	Russia	INM-CM3.0	INCM3	4 × 5°
UK Meteorological Office	UK	HadCM3 HadGEM1	HADCM3 HADGEM	2.5 × 3.75° 1.3 × 1.9°
Geophysical Fluid Dynamics Lab	USA	GFDL-CM2.1	GFCM21	2.0 × 2.5°
Goddard Institute for Space Studies	USA	GISS-AOM	GIAOM	3 × 4°
National Centre for Atmospheric Research	USA	PCM CCSM3	NCPCM NCCCS	2.8 × 2.8° 1.4 × 1.4°

B. Future Climate Data: The Coupled Model Intercomparison Project Phase 3 (CMIP3)

The scenarios derived from the coupled atmosphere-ocean GCMs enable the prediction of future climate status to adjust to the possible changes in climate forcing such as temperature rise and rainfall decline. The outputs of climate projections are available for the impact assessment studies as a common set of experiments resulting from running many GCMs, multi-model ensembles, which take into consideration the assessment of a wide range of uncertainties [14]. Reference [25] pointed out that the output from the CMIP3 which belongs to the IPCC-AR4 represent the most appropriate, largest and complete global multi-model dataset ever tried. Reference [26] also demonstrated that the CMIP3 provides an extraordinary approach of quality control data (datasets of consistent format) that utilized a range of globally identified climate models to create an easily analyzed archive of climate dataset. Moreover, the CMIP3 has been widely used around the world for impact assessment studies and has shown a good performance in capturing the future climate signals such as precipitation, temperature and other climate variables [27]-[30]. Reference [18] explained that the multi-model ensembles of the IPCC-AR4 are highly suitable for the hydrological impact studies in the Australian climate. Therefore, the multi-model ensemble approach was adopted in this study to assess the hydrological response of the Harvey River catchment to the predicted changes in future climatic conditions.

Two time periods of twenty years each, the mid (2046-2065) and late (2080-2099) of the current century, were chosen to represent the future climatic conditions. The monthly-scale future climate series of rainfall and temperature were extracted from a multi-model ensemble of 15 GCMs (Table II) of the CMIP3 under three emission scenarios A2, A1B, and B1 as defined by the IPCC [31]. For detailed information about the 15 GCMs, their features and emission scenarios, please refer to the IPCC Fourth Assessment Report [11]. In addition to the two future periods, a reference climatic period of 20 years (1981-2000) was also extracted from the multi-model ensemble. It was used to force the HBV-model to obtain the streamflow at the catchment outlet for a control run to be compared with the predicted streamflow.

C. The HBV Hydrological Model

The HBV model (Hydrologiska Byrans Vattenbalansavdelning), firstly established in Sweden, is a semi-distributed conceptual model of catchment hydrology which can simulate the daily streamflow based on the daily mean values of precipitation and temperature besides the estimated long-term monthly mean potential evapotranspiration as input data [32], [33]. Various versions of the model were applied in many regions around the world under different climate conditions, and it has been reliably proved its performance in all of these regions [34]. Furthermore, the model was used in numerous fields related to water resources such as real-time prediction, data quality control, broadening of runoff records and estimation of missing data, climate change impact studies and groundwater simulation. The HBV-model uses three storage reservoirs to depict the water balance: soil dampness storage, storage of the upper zone and a lower zone storage as illustrated in (Fig. 2) [35]. With a snow accumulation algorithm and lakes accounting algorithm, the general water balance equation becomes as shown in. (1) [36]. Additional information related to the HBV model are available in [33], [34].

$$P - E \pm \Delta S = Q \tag{1}$$

P, E, ΔS, and Q refer to the precipitation, evapotranspiration, water storing variation, and the excess runoff from the basin, respectively.

The key stimulus to use the HBV model in this study is the limited availability of climatic data in the study area. The simplicity of the input data and the robust and flexible model structure make the HBV-model a reliable tool for the climate impact assessment studies especially in the basins where the climate data are insufficient. Moreover, daily streamflow prediction offers a comprehensive idea about the hydrological changes and the status of future water resources in the catchment.

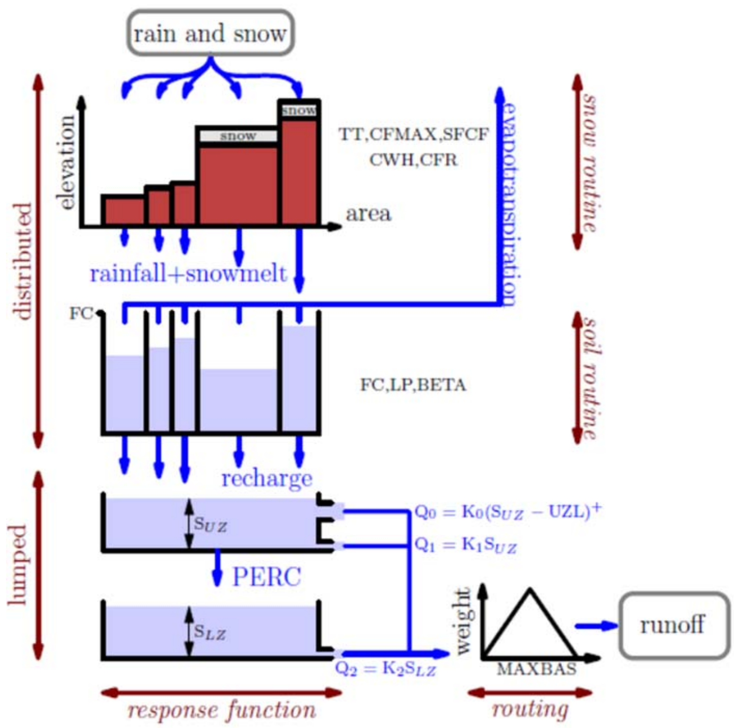


Fig. 2 A simple schematic structure of the HBV model [35]

D. Model Structure and Parameter Description

The HBV model comprises four key components: precipitation routine, soil moisture (SM), river routing and response routine [37]. Firstly, as the Harvey River catchment is a non-snow area, only rainfall will be used to represent the precipitation routine. Secondly, the SM routine, which gives an indication about the dampness of the soil, is depended on three main parameters including Field Capacity (FC), Beta (β), and the Limits of Potential evaporation (LP). The extreme soil storing volume of the catchment is represented by the parameter FC. The parameter β governs the relative involvement of precipitation to the volume of runoff at a specified deficiency of SM, while the shape of the potential evapotranspiration curve is defined by the parameter LP [38]. Finally, the surplus water of the SM routine is transformed through the response routine through two connected reservoirs

(S_{UZ} and S_{LZ}) (Fig. 2) to generate catchment runoff. These reservoirs are connected by a filtration rate (PERC) in which water percolates from the S_{UZ} to S_{LZ} at a constant proportion. The channel flow hydraulics (runoff) can be described by the transformation function parameter (MAXBAS) which calculates the computed outflow from the catchment.

IV. Methodology

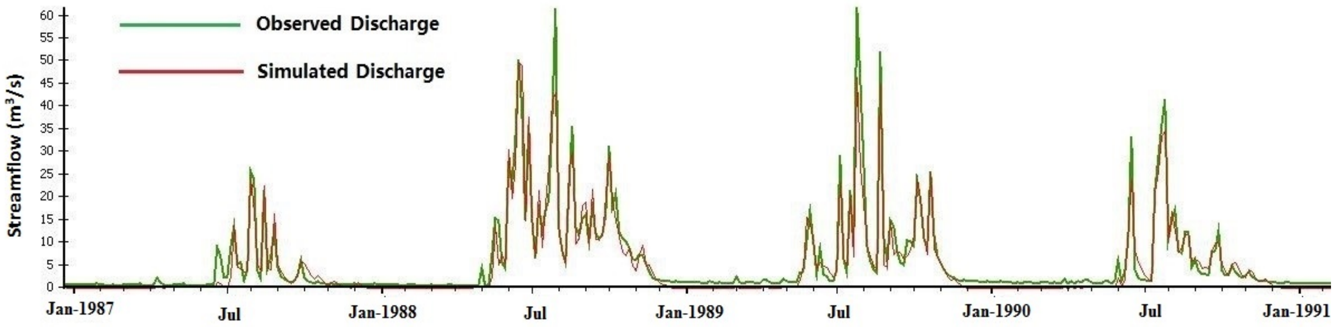
A. Data Downscaling

The impact of future climate change on catchment hydrology can be predicted by using the process-based simulation models (such as the HBV model) forced by the regional climate scenarios. Despite the improved general resolutions of the CMIP3 model, its horizontal resolution still too course to be directly applied to catchment scale impact studies. Therefore, a downscaling procedure needs to be applied to the climate output to increase their special and temporal resolutions. A plethora of downscaling techniques are available in the literature that have been employed to extract the regional-scale from the GCMs climate outputs including statistical downscaling [39], [40], dynamic downscaling [41], [42], and weather generators [43]. The highly popular stochastic weather generator, Long Ashton Research Station Weather Generator version 5.5 (LARS-WG5.5) [14], was utilized in this study to extract the local-scale daily rainfall and temperature from the monthly outputs of the CMIP3 multi-model ensemble for the mid and late this century as well as the reference period (1981-2000). This downscaling procedure examines the effect of mean climate changes, climatic variability and extreme events of climate signals to be consistently incorporated in a computationally reasonable way [44]. Therefore, it provides a cross-validation for the generated data instead of the bias correction of the monthly series which is not possible for the daily series because the precipitation is affected by the distribution of the wet and dry days. Reference [45] explained that the LARS-WG model had proven a good performance in simulating the magnitude and periodic sequence of the main climate features, and accordingly it has utilized in considerable European sites with no need to bias corrections or any other adjustments. It has also been successfully applied in many local-scale impact assessment studies in different climates around the world as a downscaling technique and has proven its applicability and its well performance [45], [14], and [15]. More details about the (LARS-WG) can be found in [45] and [14].

LARS-WG5.5 is a statistical downscaling model [46] used to generate local-scale daily time series required for climate change impact studies. It analyses the observed daily rainfall and temperature data at a specified site during a baseline period to produce a calibrated weather probability distribution parameters for that site. This method called (model calibration) in which the LARS-WG calculates relative change factors for each month considering the data in the baseline and GCMs predictions. The created parameter files are then used to generate synthetic climate data having the same statistical characteristics as the original observed data. The observed and synthetic monthly weather statistics are analyzed to evaluate the modelling performance (model validation). Finally, by perturbing the calibrated parameters for the site in consideration with the monthly-scale climate outputs of the multi-model ensemble, daily regional climate scenarios of rainfall, maximum and minimum temperature and solar radiation could be generated. The generated climate scenarios are compatible and statistically similar to the observations and the GCM predictions. The LARS-WG5.5 utilized a semi-empirical probability distribution (SED) to simulate dry and wet time series lengths as well as the monthly total precipitation. SED is defined as a separate histogram that has a fixed number of intervals of flexible lengths. The wet days are expressed as the days of precipitation of more than 0.0 mm [43]. Distribution of the continuous series lengths of wet and dry days governs the simulation of precipitation incidence, whereas the simulation of the daily maximum and minimum temperatures depends on the status of the day whether it is wet or dry. In the current versions of the LARS-WG5.5, 23 intervals are used to describe the shape of the SED compared to ten intervals used in the earlier versions [14]. Thus, this resolution offers diverse distributions of weather statistics (rainfall and temperature) to be simulated in more accurate way. A good record of daily observed climate, at least 20 years, needs to be used to obtain a robustly calibrated probability distribution parameters which are used later to generate the regional scale climate scenarios [45]. For the present study, 40 years of daily observed weather data (1961-2000) from six sites (weather stations) are used as a baseline period to create the calibrated weather parameters. These parameters were then adjusted by the delta change for the future climate scenarios derived from the multi-model ensemble that covering the proposed site to generate future daily time series of rainfall and temperature at that site. Finally, the local-scale climate outputs are used to force the HBV-model to simulate the future streamflow at Clifton Park gauging station on Harvey River.

B. HBV-Model Calibration, Validation and Parameter Estimation

For the calibration and validation processes, the HBV-model requires the daily recorded streamflow data with a variety of hydrological regimes. As mentioned earlier, daily observed streamflow data at Clifton Park gauging station on Harvey River was available for 33 years (1983-2015). In the beginning, the HBV-model was run for an initial state of one year (1983-1984) to initialize the system. Then, the model was calibrated and validated manually against the daily observed streamflow data for the periods (1984-2003) and (2004-2015) respectively. It should be noted that the HBV-model was forced with the observed rainfall, temperature and the monthly mean potential evapotranspiration during the calibration and validation periods. It can be seen here that the calibration period is almost twice the validation period, 20 years against 12 years. A possible explanation for that is after the calibration process the model should be capable of simulating large scenario datasets of the next century.



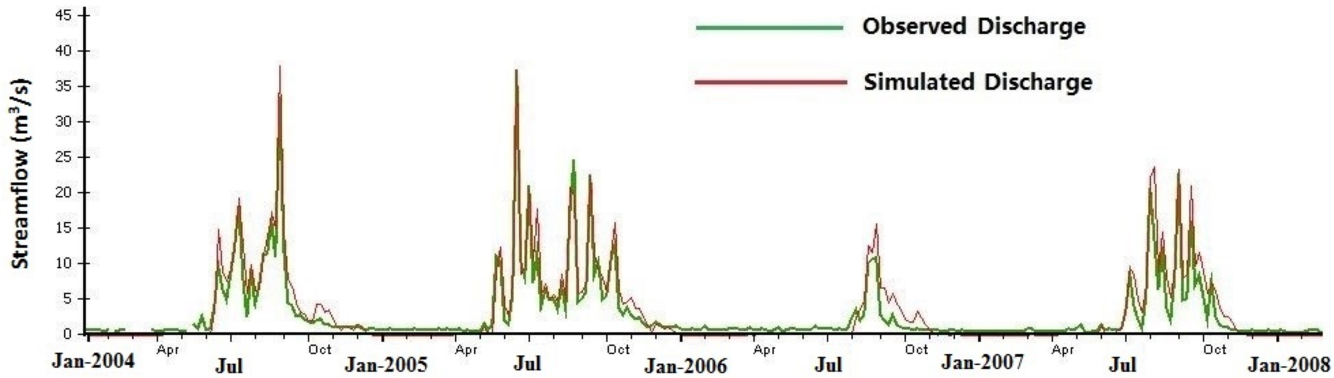


Fig. 3 Calibration (a) and validation (b) results at Clifton Park gauging station

Nine model parameters were used in the calibration processes. The manual calibration was adopted to extract the optimal set of model parameters. Table III shows the resulting set of optimal parameters and the order in which they were optimized for the Harvey River catchment. It is highly important to have a good method to evaluate the results of the calibration process [34]. Therefore, Nash-Sutcliffe efficiency (NSE) statistical criterion [47] was employed to evaluate the modelling performance. This efficiency criterion (Eq. 2) is highly popular in the hydrological modelling and impact assessment studies. For high-quality input data, NSE is normally ranged between 0.8 and 0.95 [34]. The calibration and validation results revealed a good modelling performance with NSE of 0.89 and 0.85, respectively. This indicates that the model could be used successfully to simulate the future daily runoff of the Harvey catchment. The observed and simulated streamflow hydrographs at Clifton Park gauging station on Harvey River for the calibration and validation periods are displayed in Fig. 3 where the calibration and validation hydrographs appear for selected periods (Jan. 1987-Jan. 1991 and Jan. 2004-Jan. 2008) to enable a clear comparison between the observed and simulated streamflow. Through the visual inspection of Fig. 3, it appears that the simulated discharge is fairly captured the observed discharge for both the calibration and validation periods.

$$NSE = 1 - \frac{\sum (QC - QR)^2}{\sum (QR - QR_{mean})^2} \quad (2)$$

where QC = simulated discharge and QR = observed discharge. QR mean is the mean observed discharge over the calibration period.

TABLE III
HBV MODEL PARAMETERS AND THEIR OPTIMAL VALUES RESULTING FROM THE CALIBRATION PROCESS

Parameter	Symbol	Unit	Optimal value
Rainfall correction factor	rfcf	-	0.65
Maximum soil moisture storage	FC	mm	650
Limit for potential evaporation	Lp	-	0.5
Shape coefficient	Beta	-	1.5
General correction factor for potential evaporation	ecorr	-	0.9
Recession coefficient for upper response box	Khq	1/day	1
Recession coefficient for lower response box	K4	1/day	0.1
Maximum percolation capacity	Perc	mm/day	1
Routing parameter	Maxbaz	day	1

C. Computation of Potential Evapotranspiration for the Future and Reference Periods

Potential evapotranspiration values for the reference and future periods were derived from forcing the modified Blaney-Criddle Method [48] (Eq. (3)) with the downscaled temperature data. This easy technique depends only on the daily mean temperature and the average daily percentage of annual sunshine hours [49].

$$ET^o = C\,[p\,(0.46\,T_{mean} + 8)] \quad (3)$$

where ET^o is the reference crop evapotranspiration (mm/d) as a monthly mean value. C is a correction factor depends on sunshine hours, minimum relative humidity, and daytime wind speed. T mean is the average daily downscaled temperature (°C) and p is the average daily percentage of annual sunshine hours.

TABLE IV
MEAN ANNUAL SUMS OF RAINFALL, TEMPERATURE AND POTENTIAL EVAPOTRANSPIRATION ACROSS THE HARVEY CATCHMENT, FROM THE SIX WEATHER STATIONS, FOR THE REFERENCE AND FUTURE PERIODS

	Observed 1961-2015	Reference period (1981-2000)	2046-2065			2081-2100			Changes in the mean annual values relative to the reference period (%)					
									(2046-2065)			(2081-2100)		
Variable			A2	A1B	B1	A2	A1B	B1	A2	A1B	B1	A2	A1B	B1
P (mm/year)	1165	1112	1060	1003	1050	967	945	1040	-5	-10	-6	-13	-15	-6
T (C°)	16.11	16.9	17.6	17.31	16.96	18.81	18.2	17.32	+4	+2.4	+0.5	+11.3	+7.7	+2.5
PE (mm/year)	1431	1491	1645	1630	1615	1700	1680	1635	+10	+9	+8	+14	+13	+10

All Values of Future Climate Variables Represent the Ensemble Mean of 15-Gcms

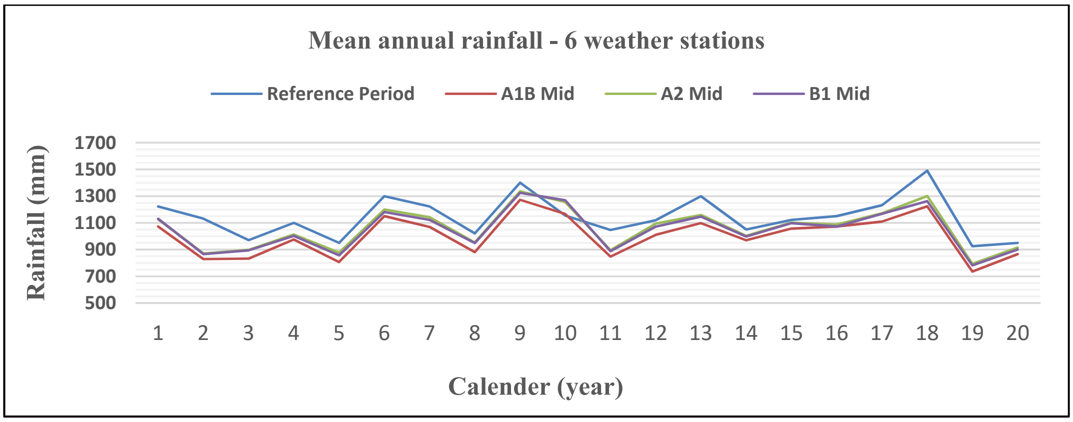


Fig. 4 (a) mid-century

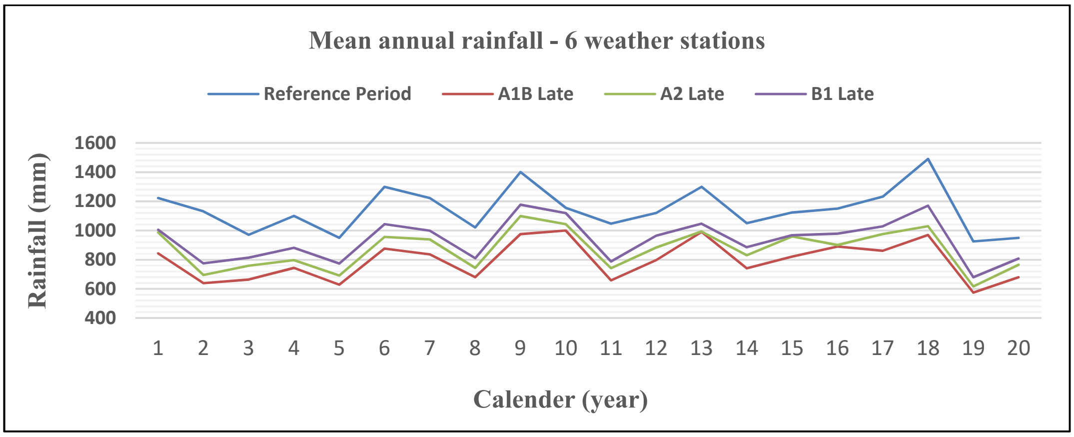


Fig. 4 (b) late-century

Fig. 4 A comparison between the mean annual rainfall during the reference and future periods under three climate scenarios (A2, A1B, and B1). The future simulated rainfall is the ensemble mean of 15-GCM

V. RESULTS AND DISCUSSION

A. Future Climate Projection

Table IV illustrates an overview of the mean annual rainfall, temperature and potential evapotranspiration for the observed, reference and future periods. Results show a clear decline in the mean annual rainfall and an increase in temperature and potential evapotranspiration for all future scenarios compared to the reference period. For mid-century, the mean annual rainfall is projected to decrease by 5%, 10% and 6% under the scenarios A2, A1B, and B1 respectively as compared with the reference period. While for late this century, the average decline in the mean annual rainfall relative to the reference period will be 13%, 15%, and 6% for the same scenarios respectively. Fig. 4 shows a comparison between the mean annual rainfall (as a mean of the six weather stations) during the reference and future periods. On the other hand, the annual mean temperature is anticipated to increase during the mid of the 21st century by 4%, 2.4%, and 0.5% for the A2, A1B, and B1 scenarios respectively as compared with the reference period. Through the end of the current century, the average increase in the annual mean temperature is projected to reach 11.3%, 7.7%, and 2.5% for the same scenarios correspondingly relative to the reference period. The projected rise in temperature values will increase the annual mean potential evapotranspiration across the Harvey basin by an approximate range of 8-14% during the future periods relative to the reference period. Therefore, the combined impact of rainfall reduction and potential evapotranspiration increase by the mid and late of the century will absolutely result in a decline in the future streamflow across the catchment.

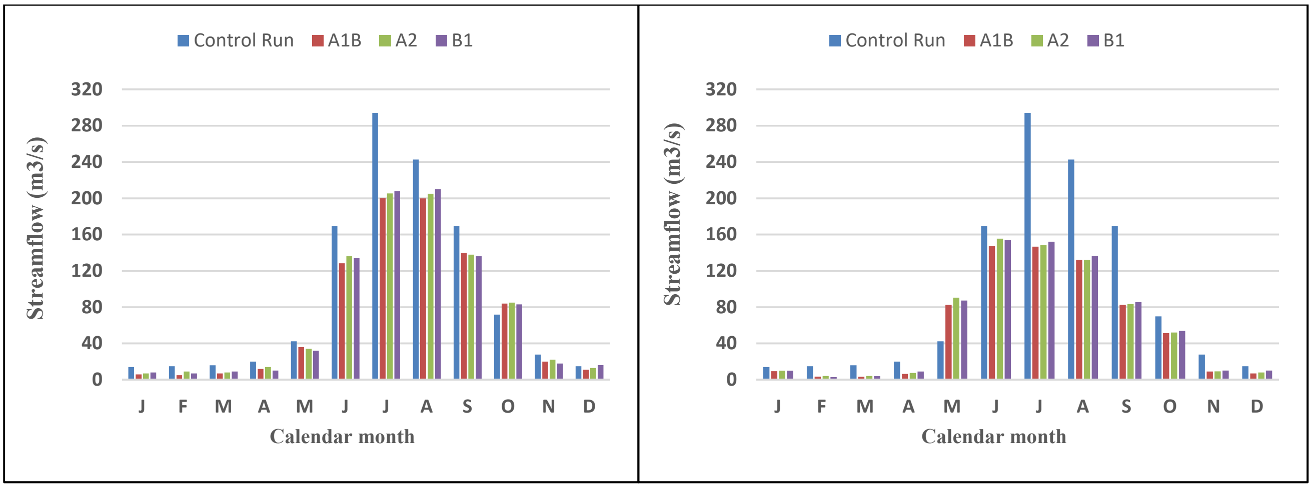
TABLE V
STREAMFLOW STATISTICS (MEAN ANNUAL AVERAGE, MEAN ANNUAL MAXIMUM AND MEAN ANNUAL MINIMUM) OF THE REFERENCE AND FUTURE PERIODS AT CLIFTON PARK GAUGING STATION

Dataset	M.A. Average (m^3/s)	M.A. Max (m^3/s)	M.A. Min (m^3/s)
Observed (1983-2015)	4.320	59.700	0.245
HBV (forced with the observed climate) (1981-2000)	4.230	61.800	0.195
HBV (forced with the Reference period) Control Run (1981-2000)	4.130	62.100	0.105
HBV (forced with the future climate scenarios)			
(2046-2065)			
A2	3.987	59.53	0.051
A1B	3.522	57.135	0.031
B1	3.955	65.325	0.121
(2080-2099)			
A2	3.214	46.385	0.032
A1B	2.377	38.605	0.021
B1	3.74	58.426	0.053

B. Future River Discharge Simulation

After the calibration process, the HBV-model was forced with the downscaled rainfall and temperature data from the mid and late-century to simulate the future daily streamflow at Clifton Park discharge station under three regional climate scenarios A2, A1B, and B1. The calibrated model was also forced with downscaled climate data from the reference period (1981-2000) as a control run to simulate the daily streamflow at the same station. The differences between the two simulations represent the projected impact of climate change on the hydrological system. A time interval of 20 years was selected for the mid and late of the 21st century to ensure unbiased contrast among the simulated and reference periods. According to [20], to consider various model simulations, three widely used streamflow statistics were calculated at Clifton Park gauging station including average streamflow, average yearly maximum and average yearly minimum as shown in Table V. These statistics are derived from four different datasets including: observed streamflow, streamflow resulting from forcing the calibrated HBV-model with the observed climate, streamflow resulting from forcing the calibrated HBV-model with the reference climate period and streamflow derived from forcing the calibrated HBV-model with the three climate scenarios A2, A1B, and B1 of the mid and late this century. The same set of model parameters (Table III) was used to simulate the future streamflow across the catchment. It is obvious from Table V that the streamflow resulting from forcing the calibrated HBV-model with the reference climate period is relatively similar to the observed streamflow as well as the streamflow resulting from forcing the calibrated HBV-model with the observed climate, particularly the mean and minimum streamflow. This implies that the bias between the observed and the downscaled reference climate periods is low, which in turn demonstrates the good performance of the LARS-WG5.5 in generating the recent and future time series, whereas the streamflow results obtained from forcing the calibrated HBV-model with the three climate scenarios produce relatively less streamflow compared to the control run.

Compared to the control run, the mean annual streamflow during the mid-century is projected to decrease by 3.5%, 14.7%, and 4.2% under the A2, A1B, and B1 scenarios, respectively, while for the late this century the mean annual streamflow shows a decreasing trend of 22.2%, 42.4%, and 9.4% under the same scenarios correspondingly. The mean annual maximum flow is also projected to decline during the mid-century by 4.1% and 8% under the A2 and A1B scenarios correspondingly, whereas the B1 scenario shows an increasing trend of 5.2% compared to the control run. By the end of the century, the mean annual maximum flow shows a declining trend of 25.3%, 37.8%, and 6% under the A2, A1B, and B1, scenarios, respectively. Finally, all the annual minimum discharges during the mid and late of the 21st century are expected to decline, except for the B1 scenario during the mid-century which shows an increment of 15.2% compared to the control run. The decline trends of annual streamflow during the mid and late of the century could be attributed to the combined impact of rainfall reduction and potential evapotranspiration increase. Fig. 5 shows a comparison between the future streamflow under the three climate scenarios and the streamflow resulting from the control run at Clifton Park gauging station. It is obvious from Fig. 5 that the future average monthly streamflow is projected to decline during the whole seasons of the year.



(a) mid-century (b) late-century

Fig. 5 Mean monthly sums of average streamflow for the control run and the three future climate scenarios (A2, A1B, and B1). The future simulated streamflow is the ensemble mean of 15-GCMs

VI. Summary and Conclusion

The hydrological response of the Harvey River catchment to the impact of future climate change during the mid (2046-2065) and late (2080-2099) of the 21st century was investigated for three regional climate scenarios A2, B1 and A1B. Future climate signals of rainfall and temperature were extracted from a multi-model ensemble of 15 GCMs of the CMIP3 which belongs to the IPCC-AR4. The LARS-WG5.5 downscaling technique was used to extract the regional scale from the output of the coupled model ensemble. It performed very well in capturing the observed climate which verifies its applicability to generate the daily future climate series for catchment-scale impact assessment. The HBV conceptual rainfall-runoff model was applied to perform the hydrologic modelling to simulate the future daily runoff at the catchment outlet. A good modelling performance was acquired during the calibration and validation processes which verify the applicability of the model to describe the future hydrological status of the catchment. Almost all GCMs predict declining trends in the mean annual rainfall across the Harvey catchment during the future periods. The mean annual potential evapotranspiration also shows increasing trends across the catchment due to the relative increase in mean annual temperature. The hydrological modelling results show decreasing trends in the future streamflow measured at Clifton Park gauging station under the three climate scenarios. Compared to the control run, the mean annual streamflow during the mid-century is anticipated to decline by 3.5%, 14.7%, and 4.2% under the A2, A1B ,and B1 scenarios respectively following a decline in mean annual rainfall of 5%, 10%, and 6%. Toward the end of the century, there could be a 22.2%, 42.4%, and 9.4% decline in mean annual streamflow under A2, A1B, and B1 climate scenarios correspondingly following a decline of 13%, 15%, and 6% in mean annual rainfall.

In conclusion, findings of the present study highlight the similar outcomes of other previous studies which have been carried out in other Australian basins and revealed a noticeable decrease in the future rainfall-runoff trends as in [4], [6], [8], [9] and [21]. Therefore, this study could be important for the Peel-Harvey Catchment Council (PHCC) and the community of the Peel-Harvey Estuary to plan efficient water strategies taking into consideration the reduction in future streamflow. The findings may also be significant to manage the usage of future water resources in the catchment such as irrigation, domestic and even drinking by considering the low flows condition, especially in the Peel-Harvey estuary region, to protect the health of the ecosystem from the risk of water reduction.

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